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Towards free-form kinetic structures

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Summary

Kinetic Reciprocal System (KRS) are a new kinetic system based on the principle of reciprocity [1] with internal pin-slot constraints. A morphogenetic procedure that can handle a set of many rigid bodies interconnected reciprocally with multiple pin-slot constraint was developed for the generation of pin-slot paths starting from the local displacements of element [2] [3].

In the design of kinetic structures, in particular when complex three dimensional and non regular configurations are involved, the functionality is frequently related to a global displacement capability of the assembly rather than the local displacements of elements. In the present paper the morphogenesis of KRS was included into a larger optimization procedure in order to translate overall design requirements into local displacements of elements. This method can be described now as a generalized procedure for the generation of free-form kinetic structures.

Keywords: Free form Kinetic Structures; Kinetic Reciprocal System

1. Introduction

A morphogenetic procedure that can handle a set of many rigid bodies reciprocally interconnected with multiple pin-slot constraint was developed for the generation of pin-slot paths starting from the local displacements of element. The resulting configuration describes the shape of the pin-slot path compatible with the local displacements of elements. The shape of the slots depend directly by the imposed local displacements, and it is univocal: a change in the local displacements determines a change in the shape of the slots and consequently a change in the shape of the elements whose the slots belong to. The potentially infinite design space of configurations that are kinematically compatible with any given local displacement should be somewhat reduced for real-world applications: beside the compatibility of the configuration other only parameter should be taken in account for the design of kinetic structures: reliability, structural issues, operational safety, geometric constraints.

It is necessary then to be able to detect the region of feasible solutions in the whole design space. In this framework, the morphogenetic procedure becomes part of an optimization procedure, where the local displacements are the design variables, and the configuration converge to the solution by reducing iteratively the errors calculated by the fitness function.

The fitness function can be the measure of different performance required by design, such as structural performance and operational safety. In the present paper the measure of the fitness are a collection of geometric parameters that are useful in creating elements with a rational shape.

2. Towards Free Form Kinetic Structures

In the context of kinetic and deployable structures new concepts typically evolve from the study of successful structures and the concepts behind them: the analysis of given configurations and the creation of new ones are two complementary aspect of the design process. When working with KRS the distinction between the two aspects vanishes: design can be better described as a true morphogenetic process, where the geometric solutions are not conceivable outside of a computational formalization of the problem. The morphogenesis approach encourages the exploration of wider design space, independently from existing typologies, focusing on the relation between problems and solutions, and triggers the emergence of unexpected configurations.

Merely abstract configurations have been generated, from the simplest ones up to very complex non regular schemes. Such configurations emerged from a purely bottom up approach, in the sense that they does not descend from a given typology but they are generated starting from the local displacement. Despite their more work should be done in order to test real-world applications, at this stage KRS appears to be a powerful tool for the generation of non regular free-form kinetic structures in a potentially infinite design space

2.1 KRS Notation

In a Pin-slot connection B_iB_j the Pin P_{ij} belonging to element B_i slides into the slot S_{ji} belonging to element B_j (Figure 1). A computational procedure allows to define the shape of the slot S_{ji}, when the amplitude of displacements and rotations of rigid bodies B_i and B_j are imposed.

The pin-slot connection between two moving rigid bodies B_i and B_j is identified in the incidence matrix each line indicating:

1) the two connected rigid bodies B_i and B_j
2) the position of the pin P_{ij} belonging to the rigid body B_i

Each Pin P_{ij} is identified by two indices *i* and *j*: index *i* indicates the element it belongs to, index *j* indicates the element the slot belongs to. Similarly each Slot S_{ji} is identified by two indices *j* and *i*: index *j* indicates the element it belongs to, index *i* indicates the element the pin belongs to.

Multiple Pin-joint connections are possible for each element in an assembly (Figure 3). A KRS configuration can then be composed of multiple elements reciprocally interconnected with multiple pin-slot constraint (Figure 4).

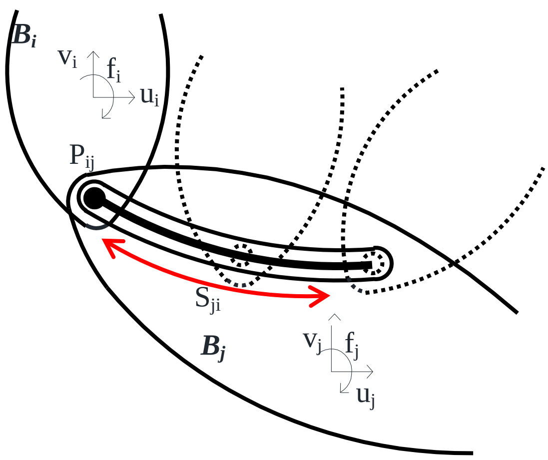


Figure 1

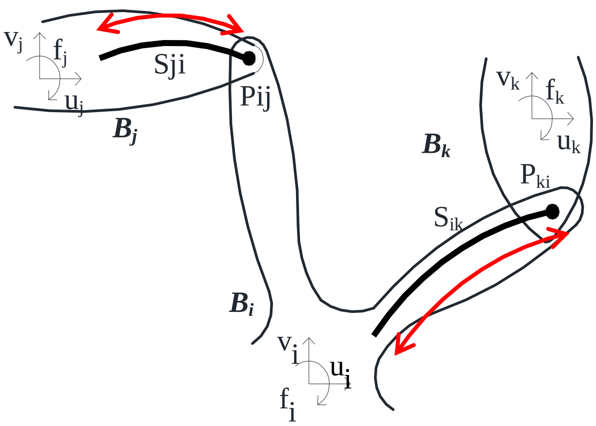


Figure 2

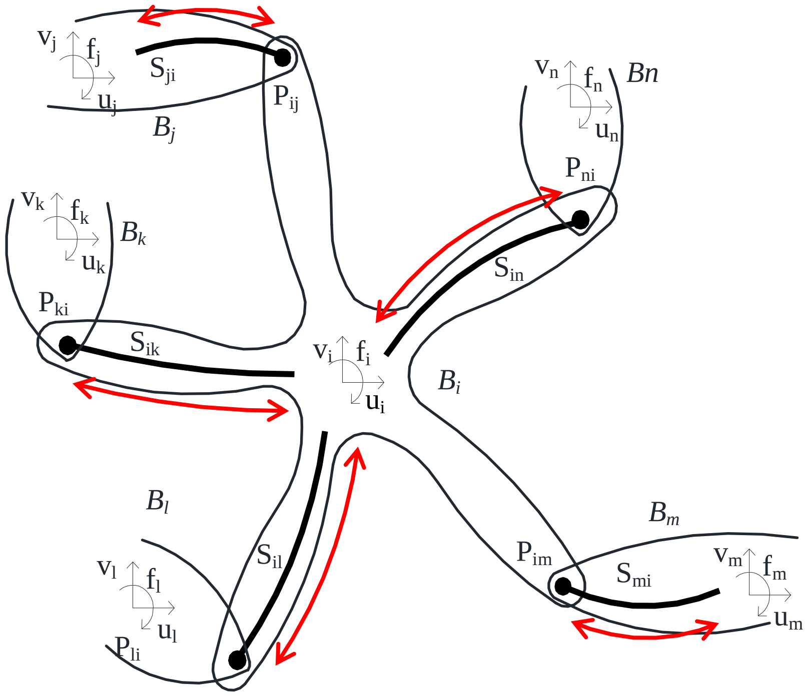


Figure 3

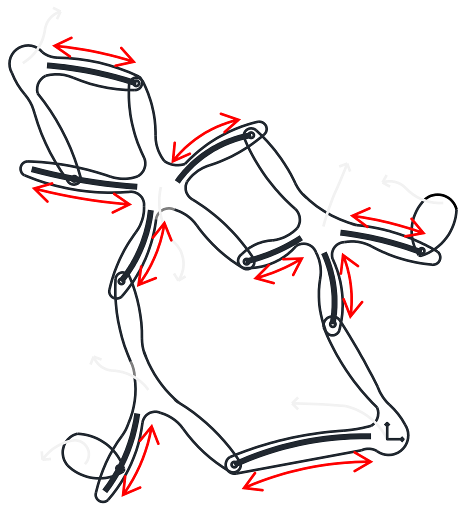


Figure 4

3. The Fitness Function

An optimization procedure was set up in order to translate overall design requirements into local kinematic parameters based on a fitness function that evaluate tentative solutions with respect to the design requirements.

The shape of each element is determined by the position of its pins P and the shape of its slots. The position of the Pins can be given as an input, while the shape of the slots depend on the local displacements. consequently, the local displacements are the design variables that determine the geometric characteristics of elements.

The geometry of the slots is evaluated on the basis of one or more of these objective by te fitness function:

1. the length of the slots should equal to a predetermined value
2. the distance between the end point of the slots and the pins should be equal to a predetermined value
3. the position of the elements in the space should fit a determined perimeter during all the stages of the deployment process.

The control on these parameters would lead to a more 'rational' and less arbitrary shapes of elements.

3.1 Length of the slots

Imposing an predetermined length of the slots indirectly control the dimension of elements: in particular, if every element possess slots with homogeneous length, their dimension would be homogeneous as well. It is possible to either establish an arbitrary value of length in advance, or to calculate the mean length of all the slots in the assembly at each step of the optimization procedure and use this value as a reference length.

In the first acse, if the imposed length is l_{ref} the measure of the fitness is:

$$fit1a = \sum_{j=1}^{N} \left| l_j - l_{ref} \right| \tag{1}$$

where l_j is the length of the slot S_{ij}.

In the latter case if the reference length is calcluated ate every step n the basis of the mean length of all the lots in the assembly, the measure of the fitness is:

$$fit1 = \sum_{j=1}^{N} \left| l_j - \frac{\sum_{j=1}^{N} l_j}{N} \right| \tag{2}$$

where l_j is the length of the slot S_{ij} and N is the total number of slots.

3.2 Distance between the end point of the slots and the pins

This objective allows to control the distance between the end points of the Slots and the Pins. The control on this value allows to influence the 'compactness' of elements, because it is a measure on how slots and pins are close between each other. This value is calculated as:

$$fit2 = \sum_{j=1}^{N} d_j \tag{3}$$

where dj is the distance between a Pin and a Slot inside the element B_i (Figure 5)

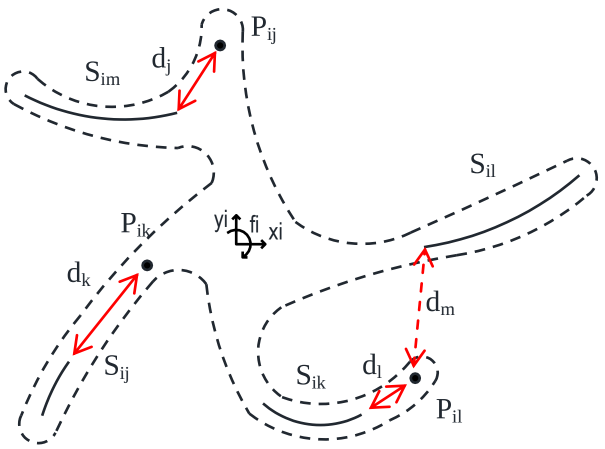


Figure 5

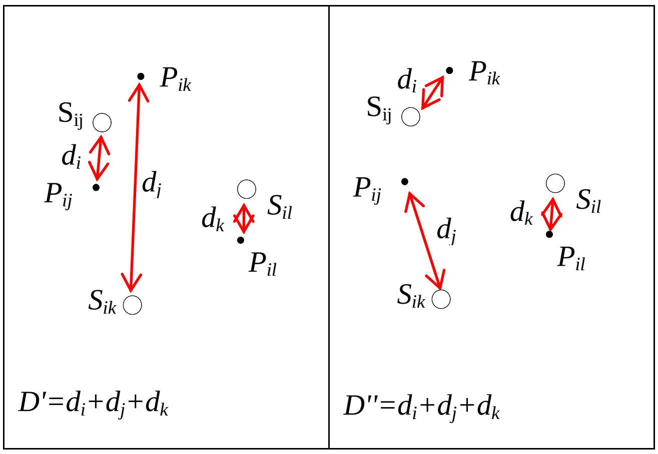


Figure 6: D'>D''

3.2.1 Ballroom algorithm

Multiple combinations can exist between the 'couples' of Pins and Slots we choose to calculate the distance on. In Figure 5 we can observe that the Pin P_{il} can be connected to either Slot S_{ik} or slot S_{il}; this consideration is valid for each Pin and Slot couple. Which couple should we choose between al the possible combinations?

Let consider inside each element a set of Pins Pi including Pins *Pij Pik Pil* and a set of slots S*i* including S_{ij} S_{ik} S_{il}. The 'ballroom' algorithm enable to choose between all the combinations of Pins and Slots the one with the minimum total distance between the couples of Pins and Slots. A Genetic Algorithm is used and the fitness variable is the vector of the combination of elements, and the fitness function returns the value of the total distance between the couples.

It is possible to detect the minimum distance combination with a bruteforce algorithm, that calculates all the possible combinations between pin and joints. However the number of possible combinations increases exponentially with the number of elements in the set of Pins and Slots, and especially if the number of elements in the sets is bigger than four it is convenient to use the ballroom algorithm.

3.3 Position of elements in all the steps of the deployment process.

This objective allows to define arbitrary perimeters for three stages of a kinetic structure: the initial position, the deployment phase, the final position. If the elements falls outside these perimeters a penalty fator is introduced. The perimeter d1 encloses the structure in the initial position, the perimeter d2 encloses the structure in the deployment process, the perimeter d3 encloses the structure in its final position. Either regular (Figure 7) or non regular (Figure 8) perimeters can be defined.

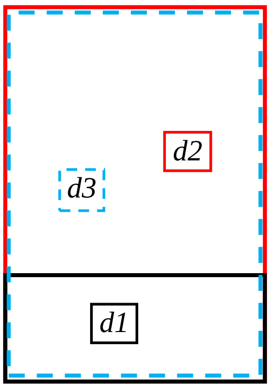


Figure 7: regular perimeters

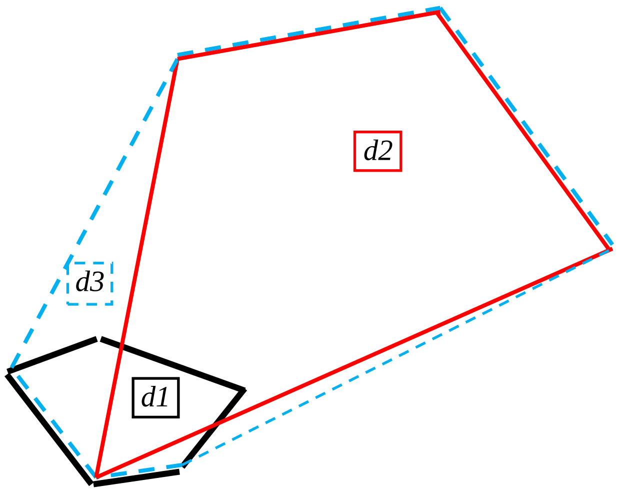


Figure 8: non regular perimeters

4. Benchmark on a Six Bars Assembly

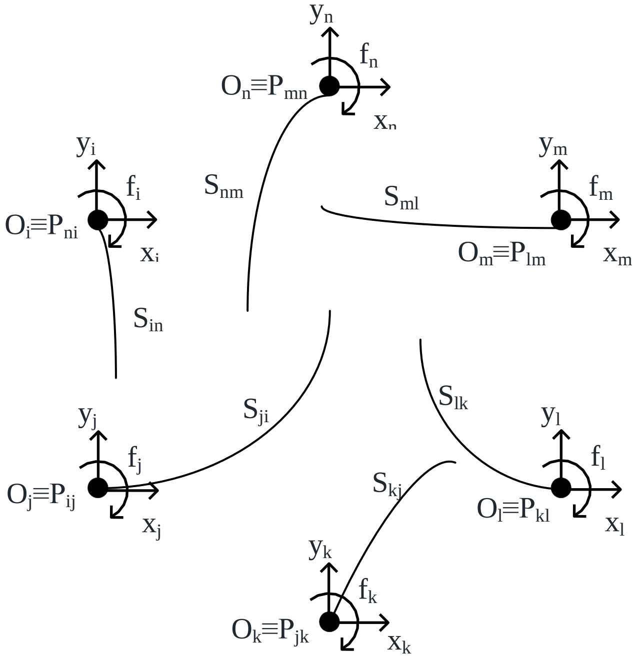


Figure 9

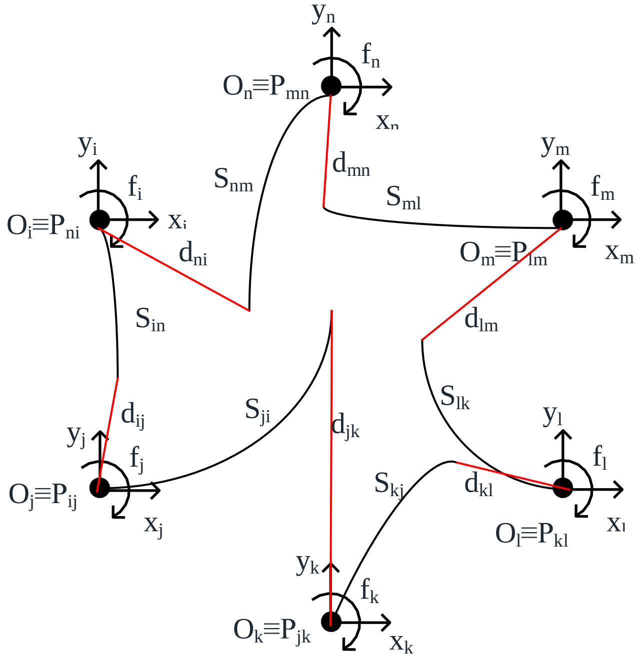


Figure 10

A benchmark is run on the six bars assembly of Figure 9. The assembly is defined by six rigid bodies B_i B_j B_k B_l B_m B_n with origin respectively in O_i O_j O_k O_l O_m O_n. The elements are connected accordingly to the following incidence matrix

B_i	B_j	P_{ij}		S_{ji}
B_j	B_k	P_{jk}		S_{kj}
B_k	B_l	P_{kl}	$\longrightarrow$	S_{lk}
B_l	B_m	P_{lm}		S_{ml}
B_m	B_n	P_{mn}		S_{nm}
B_n	B_i	P_{ni}		S_{in}

Column one and two indicate the two interconnected element. The first column indicates the element which the Pin belong to, the second columns indicate the element the Slot belong to. The third column indentifies the Pin P_{ij}. Each line would produce a slot belonging to the element in the second column S_{ji}.

The configurations reported in the benchmarks represent the initial position of the configuration before the displacement begins (rotations and translations). Each fitness parameter is calculated independently, however they can be combined in an unique fitness value. Also, it is possible to limit the design variables to the displacements of a selected set of elements, and the displacements could be limited only to selected types. in the following examples the design variables include the local displacement of each element and include both rotation and translation.

4.1 Length of the slots benchmark

In this benchmark the fitness function calculates the length of the slots and compare it to a given value. In Figure 11 the imposed length is 1.2 units, in Figure 12 the length is imposed equal to 0.6 units and in Figure 13 the imposed length is 0 units. In this latter case the slots become hinges instead, demonstrating that the algorithm can be generalized to handle this constraint too.

4.2 Distance between the end point of the slots and the pins

In this benchmark the fitness function calculates the distance between the end points of the slots and the pins in each element B_i. In Figure 14 the imposed length is 0.9 units, in Figure 15 the length is imposed equal to 0.45 units and in Figure 16 the imposed length is 0

4.3 Enclosing perimeters

In this benchmark the fitness function applies a penalty factor if the elements does not fit inside some given perimeters during all the stages of the motion.

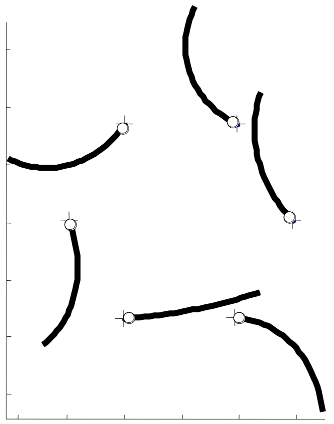


Figure 11: configuration with slots length =1.2 units

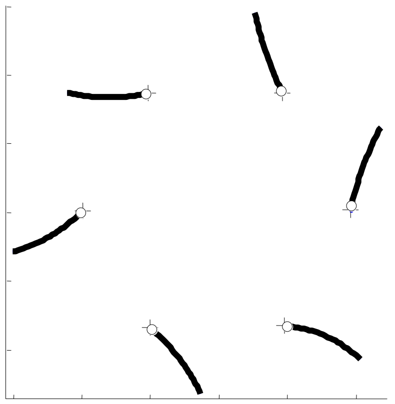


Figure 12: configuration with slots length =0.6 units

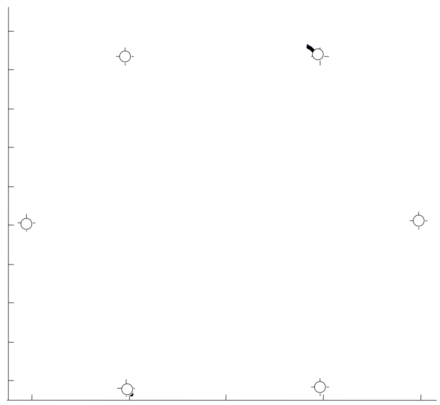


Figure 13 : configuration with slots length =0 units

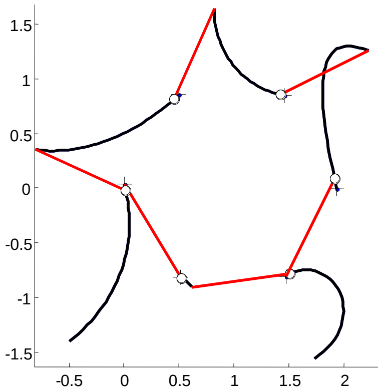


Figure 14: configuration with distance slots-pin=0.9 units

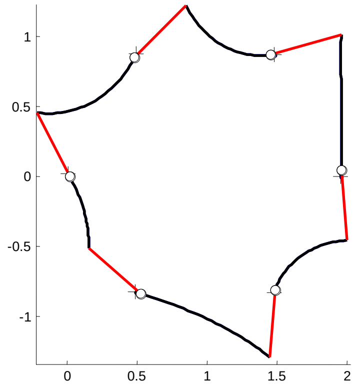


Figure 15 : configuration with distance slots-pin=0.45 units

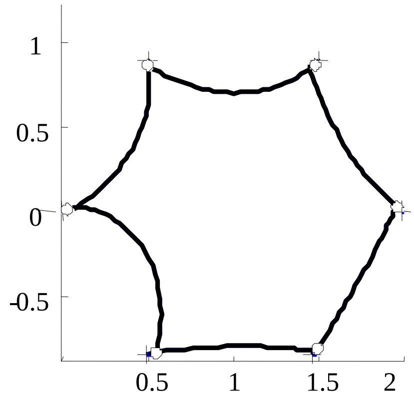


Figure 16: configuration with distance slots-pin=0 units

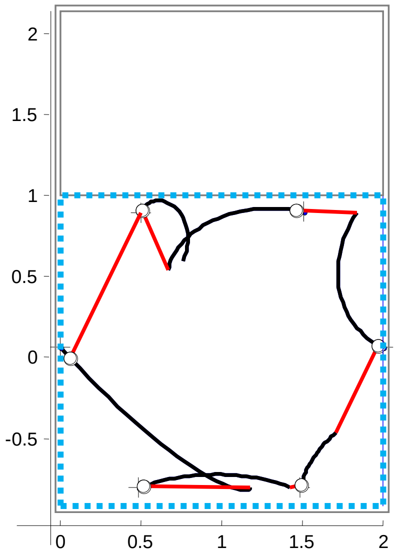


Figure 17: starting postition

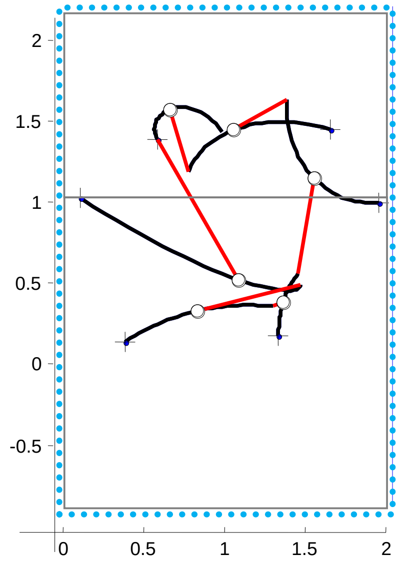
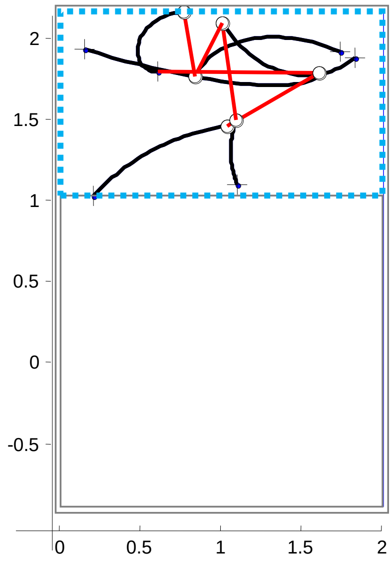


Figure 18: deployment phase



Fgiure 19: end position

5. Application

The optimization procedure described above can was applied to an example of free form kinetic structure. The problem is inspired by the six bars array of Figure 20-22: the kinetic structure was designed using the morphogenetic algorithm of KRS and a working prototype was built [4]. The structure has one degree of freedom and its elements rotates in the plane: from the initil position (Figure 20) to the final position (Figure 22) each element rotate of approximately 60 degrees around the z axis.

Each element possess three arm each hosting a slot (S_{il}, S_{ik}, S_{ij}). Eeach arm host closely to the end point of each slot three pins (P_{il}, P_{ik}, P_{ij}). The shape of the elements (Figure 19) in this configuration is very rational because the Pins sit close to the slots, and it does not require to use much more materials to connect pins and slots inside each element.

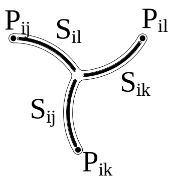


Figure 20:

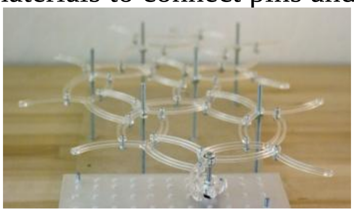


Figure 21

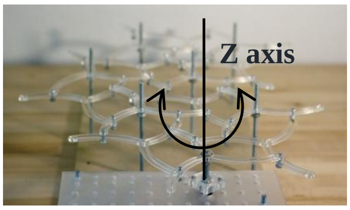


Figure 22

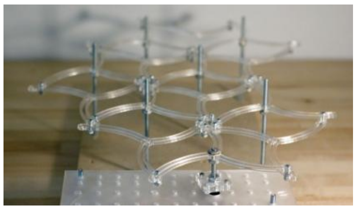


Figure 23

Element B_i

The initial idea is to turn this planar mechanism into a spatial mechanism, i.e. each element sits at different heights. However, if the elements continue to rotate around the z axis each slots would develop in the xy plane and additional segments d_{ij} d_{jk} d_{kl} d_{lm} d_{mn} d_{ni} would be added to connect the pins and the slots of each element at different heights.

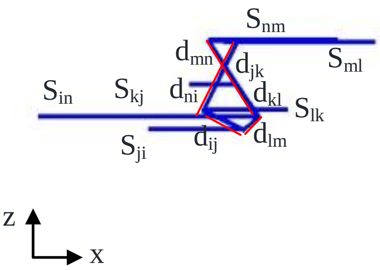


Figure 24

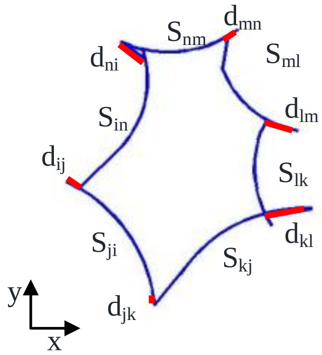


Figure 25

In order to obtain a more rational shape of the elements it would be necessary that the slots develops with their end points close to the pins. In this way no additional segments would be needed to connect the pins and the slots, resulting in a more rational and harmonious shape of elements.

The problem is set up by locating the initial position of elements along a free-form shape (Figure 25). A displacement vector is then imposed to each element. In this case, the imposed displacement moves the elements to a plane (Figure 26).

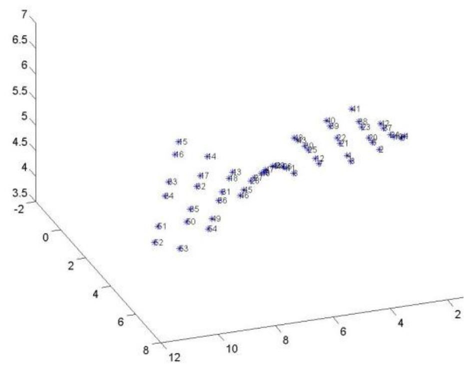


Figure 26: starting point of displacement

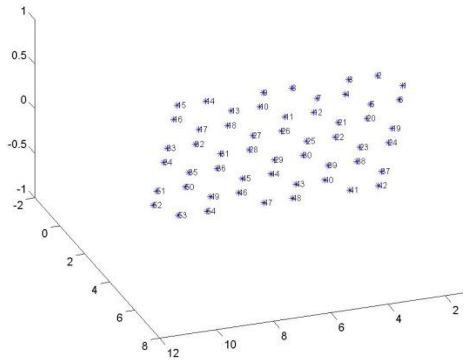


Figure 27: end point of displacement for each element

The design variables are the rotation of each element around the x y and z axis, so it becomes a spatial rotation. The fitness function calculates the distance between the end point of the slots and the pins inside each element.

The Genetic Algorithm finds the values of the spatial rotation of each element such that the distance between the end points of their slots and pins is minimized.

Figures 27-32 shows the optimal configurations of the set of interconnected rigid bodies that moves in the space from the starting position of Figure 25 to the end position of Figure 26

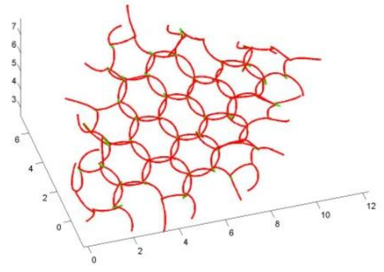


Figure 28

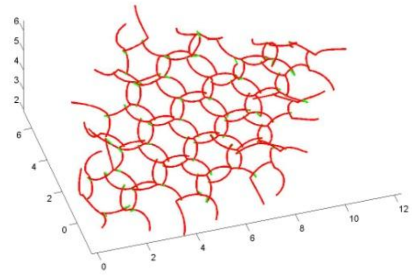


Figure 29

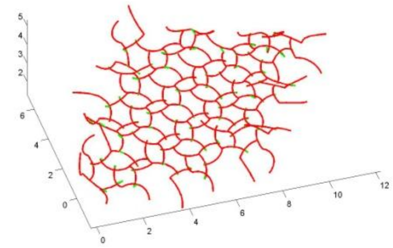


Figure 30

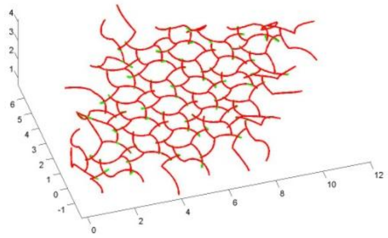


Figure 31

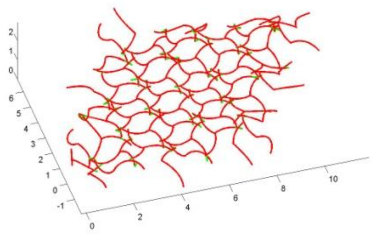


Figure 32

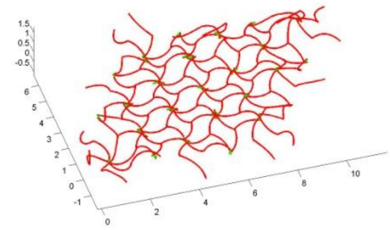


Figure 33

6. Conclusions

In the present paper the morphogenesis of KRS was included into a larger optimization procedure in order to translate overall design requirements into local displacements of elements. This method can be described now as a generalized procedure for the generation of free-form kinetic structures.

References

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